ApJ in press

Modeling the Optical Afterglow of GRB 030329

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ABSTRACT

The best-sampled afterglow light curves are available for GRB 030329. A distinguishing feature of this event is the obvious rebrightening at around 1.6 days after the burst. Proposed explanations for the rebrightening mainly include the two-component jet model and the refreshed shock model, although a sudden density-jump in the circumburst environment is also a potential choice. Here we re-examine the optical afterglow of GRB 030329 numerically in light of the three models. In the density-jump model, no obvious rebrightening can be produced at the jump moment. Additionally, after the density jump, the predicted flux density decreases rapidly to a level that is significantly below observations. A simple density-jump model thus can be excluded. In the two-component jet model, although the observed late afterglow (after 1.6 days) can potentially be explained as emission from the wide-component, the emergence of this emission actually is too slow and it does not manifest as a rebrightening as previously expected. The energy-injection model seems to be the most preferred choice. By engaging a sequence of energy-injection events, it provides an acceptable fit to the rebrightening at ~ 1.6 d, as well as the whole observed light curve that extends to ~ 80 d. Further studies on these multiple energy-injection processes may provide a valuable insight into the nature of the central engines of gamma-ray bursts.

Subject headings: gamma rays: bursts — ISM: jets and outflows

1. Introduction

GRB 030329, with a fluence as large as $\sim 1.18 \times 10^{-4}$ ergs/cm^2 (Ricker et al. 2003; Vanderspek et al. 2004) and being in the top 1% of all detected gamma-ray bursts, is a watershed event in the field. Lying at a redshift of $z = 0.1685$ (Greiner et al. 2003a), it is the closest classical gamma-ray burst (GRB) to date. For the first time, an unambiguous underlying type Ic supernova was revealed spectroscopically about one week after the trigger (Hjorth et al. 2003; Stanek et al. 2003; Matheson et al. 2003). This already suspected connection between GRBs and core-collapse supernovae, which was first hinted at by the amazing coincidence of GRB 980425 and SN 1998bw (Galama et al. 1998), is now firmly established, finally shedding light on the previously unclear nature of long GRBs. Additionally, the radio afterglow of GRB 030329 was resolved with Very Long Baseline Interferometry observations, leading to a direct measurement of the size of a cosmological GRB remnant for the first time (Taylor et al. 2004, 2005). The observed expansion rate of the remnant, being generally consistent with theoretical expectations, provides valuable evidence for the standard fireball model (Oren, Nakar, & Piran 2004; Granot, Ramirez-Ruiz, & Loeb 2004). Furthermore, a polarization light curve of unprecedented detail was obtained (Greiner et al. 2003b). Observed polarization, with significant variability, is at the percent level, casting light on the structure of the jet, the configuration of internal magnetic field, and other micro-physics of the blastwave.

So far, GRB 030329 is also the event with the most copious afterglow data, due to its extremely bright afterglow. A very detailed R-band afterglow light curve has been compiled by Lipkin et al. (2004). The available R-band data spans from ~ 0.05 d to ~ 80 d, with a total of 1644 points, which is unprecedented. The R-band light curve shows many interesting features. First, an obvious bending appears at $t \sim 0.5$ d, which can be satisfactorily interpreted as a jet break (Uemura et al. 2003). Secondly, the afterglow rebrightened significantly and rapidly at $t \sim 1.6$ d. Thirdly, obvious variability has also been observed during $t \sim 2.3$ — 7 d. Finally, the afterglow rebrightened markedly again at $t > 20$ d as compared with the simple power-law extrapolation, which in fact reflects the contribution from the underlying supernova, emerging as the GRB afterglow itself fades away. The copious observations and the interesting afterglow behavior have made GRB 030329 an amazing example, attracting the attention of many authors.

Berger et al. (2003) suggested that the rebrightening at $t \sim 1.6$ d can be explained by adopting a two-component jet model. In their framework, the central, narrower, faster jet can account for the light curve break at $t \sim 0.5$ d, while the outer, wider, slower jet, which intrinsically carries more kinetic energy, will finally outshine the former and naturally give birth to the observed rebrightening at ~ 1.6 day. On the other hand, Granot, Nakar, &

Piran (2003) suggested another model for the rebrightening. They proposed that a refreshed shock, i.e., energy injected into the blastwave by an additional shell from the central engine, can boost the brightness. Only simplified analytical approaches have been devoted to this important question until now. It is thus worthwhile to revisit the issue by carrying out realistic and more accurate numerical calculations.

In this study, we will model the R-band afterglow light curve of GRB 030329 numerically, paying special attention to the rebrightening at $t \sim 1.6$ d. We base our calculations on three candidate models, i.e., the density-jump model, the two-component jet model, and the energy-injection model. Our paper is organized as follows. We first describe the details of our calculations, including the dynamics and the radiation process in §2. We then examine the observed R-band light curve in the framework of the three models respectively in §3. We discuss our results and present our conclusions in §4.

2. Dynamics and Radiation Process

In the standard fireball model, afterglows are produced when the fireball, either isotropic or collimated, ploughs through the circumburst medium, producing a strong blastwave that accelerates swept-up electrons (For recent reviews, see van Paradijs, Kouveliotou, & Wijers 2000; Mészáros 2002; Piran 2004; Zhang & Mészáros 2004). Afterglows are observed when synchrotron photons are emitted by these accelerated electrons (Sari, Piran, & Narayan 1998), although inverse Compton scattering may also play a role in some cases (Wei & Lu 2000a; Sari & Esin 2001). The conditions involved in GRB afterglows are complicated. For example, the blastwave may be either highly radiative or highly adiabatic, and may experience the ultra-relativistic phase and the Newtonian phase sequentially. In case of jets, the remnant may expand laterally or not. The circumburst medium may be either homogeneous or wind-like. The shock-accelerated electrons may be adiabatic or cool in real time. The final afterglow light curve also strongly depends on the frequency that we are observing at. Simple analytical results are available for the whole process of the afterglow, but detailed expressions can be given only when the conditions involved are highly simplified (Zhang & Mészáros 2004).

On the other hand, there are also some factors that cannot be easily incorporated into analytical considerations, among them is the equal arrival time surface effect (Waxman 1997; Sari 1997; Panaitescu & Mészáros 1998). This ingredient will definitely affect the smoothness and variability of GRB afterglow light curves significantly. Although analytic expressions for equal arrival time surfaces can be derived under some simplified assumptions (Bianco & Ruffini 2005), their exact effects on the light curve still cannot be included in usual analytical

expressions. Numerical evaluation will be the only efficient solution in some circumstances, especially when rapid variability is involved.

A simple model that can be applied under various conditions addressed above, and which is also very convenient to solve numerically, has been developed by Huang et al. (1999, 2000a, 2000b; Huang & Cheng 2003). We will use this model for the current study. In this model, the evolution of the bulk Lorentz factor (γ) of the shock-accelerated circumburst medium is given by (Huang, Dai, & Lu 1999),

$$\frac{d\gamma}{dm} = -\frac{\gamma^2 - 1}{M_{\rm ej} + \epsilon m + 2(1-\epsilon)\gamma m}, \tag{1}$$

where m is the mass of swept-up medium and $M_{\rm ej}$ is the initial mass of the fireball. ϵ is the radiative efficiency, which equals 1 for a highly radiative blastwave, and equals 0 in the adiabatic case. Equation (1) has the virtue of being applicable in both the ultra-relativistic and the non-relativistic phases (Huang et al. 1999). For collimated outflows, the lateral expansion is realistically described by (Huang et al. 2000a, 2000b),

$$\frac{d\theta}{dt} = \frac{c_{\rm s}(\gamma + \sqrt{\gamma^2 - 1})}{R}, \tag{2}$$

with the comoving sound speed $c_{\rm s}$ given by

$$c_{\rm s}^2 = \hat{\gamma}(\hat{\gamma} - 1)(\gamma - 1)\frac{1}{1 + \hat{\gamma}(\gamma - 1)}c^2, \tag{3}$$

where θ is the half-opening angle, R is the radius, and $\hat{\gamma} \approx (4\gamma + 1)/(3\gamma)$ is the adiabatic index.

To calculate synchrotron radiation from shock-accelerated electrons, a realistic electron distribution function (Dai, Huang, & Lu 1999; Huang & Cheng 2003) that takes into account the cooling effect (Sari, Piran, & Narayan 1998) will be adopted. Especially, since we will assume in our calculations a value smaller than 2 for the electron power-law distribution index, p, the minimum Lorentz factor of electrons should be given by

$$\gamma_{\rm e,min} = \left[\left(\frac{2-p}{p-1}\right)\left(\frac{m_p}{m_e}\right)\epsilon_e(\gamma - 1)(\gamma_{\rm e,max} - 1)^{p-2}\right]^{1/(p-1)} + 1, \quad (1 < p < 2), \tag{4}$$

where $m_{\rm p}$ and $m_{\rm e}$ are masses of proton and electron respectively, $\gamma_{\rm e,max} = 10^8(B'/1{\rm G})^{-1/2}$ is the maximum Lorentz factor of electrons, with B' being the comoving magnetic field strength. Equation (4), which slightly differs from the expression given by Dai & Cheng (2001) for electrons with a flat spectra, is more general since it is applicable even in the deep Newtonian phase, when $\gamma_{\rm e,min}$ is less than a few and most electrons are no longer ultra-relativistic (Huang & Cheng 2003).

3. Numerical Results

In this section we study the optical afterglow of GRB 030329 numerically, paying special attention to its rebrightening at $t \sim 1.6$ d. We take the R-band light curve provided by Lipkin et al. (2004) as the observed template, which has the advantage of having the widest time-span, the most prolific data points, and also the least systematic discrepancy. However, the original data of Lipkin et al. includes contribution from the host galaxy and the underlying supernova. The host galaxy magnitude is $R = 22.66$ (Gorosabel et al. 2005). Using the observed light curve of SN 1998bw as a template (Galama et al. 1998; Zeh, Klose, & Hartmann 2004), the brightness of the supernova has also been determined by Zeh, Klose, & Hartmann (2005). A pure R-band afterglow light curve is thus available for GRB 030329 after subtracting these extra components and correcting for Galactic extinction (according to Schlegel, Finkbeiner, & Davis 1998). Here we use the pure afterglow light curve as the final template. We will try to fit it in light of three detailed models which all have the potential of producing the rebrightening: the density-jump model, the two-component jet model, and the energy-injection model.

3.1. Density-Jump Model

A possible model that can potentially produce a rebrightening in GRB afterglows is the so called density-jump model. Analytically it has been shown that when the blastwave encounters a sudden density increase in the medium, the afterglow emission will be enhanced temporarily (Lazzati et al. 2002; Nakar & Piran 2003; Dai & Wu 2003; Tam et al. 2005). We have examined GRB 030329 in this framework. The jet involved is assumed to have an initial half-opening angle of $\theta_{\rm N} = 0.05$, with an isotropic kinetic energy $E_{\rm iso} = 3.5 \times 10^{53}$ ergs, and an initial Lorentz factor $\gamma_0 = 300$. Other parameters are taken as: electron energy ratio $\epsilon_{\rm e} = 0.1$, magnetic energy ratio $\epsilon_{\rm B} = 0.01$, electron spectral index $p = 1.9$, and the luminosity distance $D_{\rm L} = 0.8$ Gpc (this value is derived by assuming a cosmology of $H_0 = 71$ km/s/Mpc, $\Omega_{\rm M} = 0.27$, $\Omega_\Lambda = 0.73$). The number density of the circumburst medium is initially assumed to be $n = 2$ /cm^3, but it increases abruptly by a factor of 10 or 100 at the observer's time $t = 1.1 \times 10^5$ s. The final results are illustrated in Figure 1.

In our theoretical light curves no obvious rebrightening can be seen. The analytically predicted temporary rebrightening is smeared out by the equal-arrival time surface effect. Additionally, well after the density-jump, the afterglow flux decreases more steeply. For a higher density contrast, the fading of the afterglow is even more obvious. This trend is consistent with the results of Tam et al. (2005) for cylindrical jets. Our results are also consistent with the other authors' conclusion that density fluctuations are usually unable

to produce either a sharp variation or a steep increase in the light curve (Piran, Nakar, & Granot 2003; Nakar & Piran 2003).

Figure 1 shows clearly that the density-jump model can not explain the basic feature of GRB 030329, the rebrightening at 1.6 d. It even can not explain the observed emission at $t \geq 2 \times 10^5$ s. A simple density-jump explanation thus can be completely excluded for GRB 030329.

3.2. Two-Component Jet Model

The simplest jet model involves a homogeneous conical outflow. However, in reality jets can have complicated structures (Mészáros, Rees, & Wijers 1998; Dai & Gou 2001; Rossi, Lazzati, & Rees 2002; Kumar & Granot 2003; Salmonson 2003; B. Zhang et al. 2004; W. Zhang, Woosley, & Heger 2004). A two-component jet consists of two components: a narrow ultra-relativistic outflow and a wide but mildly relativistic ejecta, which are usually assumed to be coaxial (Frail et al. 2000; Ramirez-Ruiz, Celotti, & Rees 2002; Berger et al. 2003; Sheth et al. 2003; Huang et al. 2004; Peng, Königl & Grant 2005; Wu et al. 2005). It has been suggested that the two-component jet model can give a satisfactory explanation to the multiband observations of GRB 030329 (Berger et al. 2003; Sheth et al. 2003): the gamma-ray and early afterglow emission come from the narrow component, while the radio and optical afterglows beyond ~ 1.5 days are produced by the wide component. The half-opening angles of the two components are even estimated as $\sim 5^{\mathrm{o}}$ and $\sim 17^{\mathrm{o}}$ respectively (Berger et al. 2003). The total intrinsic kinetic energy of the whole jet is perfectly consistent with the standard energy reservoir hypothesis (Frail et al. 2001; Panaitescu & Kumar 2001; Bloom, Frail, & Kulkarni 2003).

We have tried to fit the R-band light curve of GRB 030329 by using the two-component jet model numerically. The best results are illustrated in Figure 2. In our calculations, we evaluate the parameters as follows. For the narrow component, the initial half-opening angle is $\theta_{0,\mathrm{N}} = 0.05$, isotropic kinetic energy $E_{\mathrm{N,iso}} = 3.0 \times 10^{53}$ ergs, and initial Lorentz factor $\gamma_{0,\mathrm{N}} = 300$. For the wide component, these parameters are $\theta_{0,\mathrm{W}} = 0.15$, $E_{\mathrm{W,iso}} = 3.0 \times 10^{53}$ ergs, $\gamma_{0,\mathrm{W}} = 30$ respectively. Other parameters that are common to the two components are: $\epsilon_{\mathrm{e}} = 0.1$, $\epsilon_{\mathrm{B}} = 0.01$, $n = 2$ /cm^3, $p = 1.9$, and $D_{\mathrm{L}} = 0.8$ Gpc. Some of our parameters differs from those recommended by Berger et al. (2003; also see Friedman & Bloom 2005). For example, we need an $E_{\mathrm{N,iso}}$ that is larger by about a factor of 10, since in our numerical calculations we take into account the deceleration of the blastwave before the usual deceleration radius. Also our $\theta_{0,\mathrm{N}}$ is smaller, since the lateral expansion plays a subtle role in the process.

Figure 2a shows clearly that the narrow component can give an acceptable fit to the observed light curve when $t < 10^5$ s, also the wide component emission can give a marginally acceptable explanation for observations of $t > 2 \times 10^5$ s. However, when the emission from the two components is added together, the final light curve is disappointingly too smooth at $10^5\mathrm{s} < t < 2 \times 10^5$ s. In other words, the model cannot reproduce the observed rapid rebrightening at $t \sim 1.6$ d. The key problem is that the wide component emission peaks at $\sim 4 \times 10^3$ s, too early as compared with observations. Additionally, the dotted line in Figure 2a is very smooth at around the peak, so that it obviously has no hope to account for the rapid variability even if the peak were properly postponed.

The difficulty of a simple two-component jet model to explain the rapidness of such a rebrightening has been realized by Huang et al. (2004) in an earlier study. They went further to conjecture that some subtle details, such as the overlap effect of the two components, may help to relax the difficulty (note that in the calculations of Huang et al. (2004), it was assumed that $t = 0$ at the deceleration radius). In Fig 2b, we have re-calculated the theoretical light curve by assuming that the wide component is a hollow cone since its central portion is occupied by the narrow component. In this case, the peak of the wide component emission is significantly postponed as expected. However, the light curve becomes even smoother near the peak. This modification is thus essentially of no help in accounting for the rapidness of the rebrightening.

In fact, the failure of the two-component jet model to reproduce the rapid rebrightening at $t \sim 1.6$ d is not a surprize. In Berger et al. (2003), we notice that the rebrightening is still not rapid enough even in their idealized analysis. A similar trend can also be seen in a superceding detailed study on the two-component jet model by Peng, Königl, & Granot (2005). In our current study, the equal arrival time surface effect and the realistic dynamical transition at the deceleration radius add together to further suppress the variability. Additionally, if a more complex dynamical model as suggested by Granot et al. (2002) is adopted, things will surely get even worse. In short, although the two-component jet model can give a feasible explanation for the overall R-band light curve, it is not satisfactory in reproducing the rapid rebrightening at $t \sim 1.6$ d. However, given that the existence of two jets has been clearly indicated by two breaks (at ~ 0.5 d and ~ 5.5 d respectively) in the observed light curve, the two-component jet model is still an attractive idea for GRB 030329. We will further discuss some schemes that may ameliorate this idea in the final section of our paper.

3.3. Energy-Injection Model

Although typical long GRBs last for only tens of seconds, the central engine can actually be active for much longer, supplying energy into the blastwave during the afterglow phase. This can naturally lead to the rebrightening of GRB afterglows. Evidence for such activities has been found in a few events (Piro 1998; Dai & Lu 1998, 2001; Zhang & Mészáros 2001, 2002; Bjornsson et al. 2002; Bjornsson, Gudmundsson, & Johannesson 2004; Burrows et al. 2005; King et al. 2005; Watson et al. 2005; Cusumano et al. 2005).

Energy injection can be accomplished in various forms, on very different timescales. If the central engine is a rapidly rotating millisecond pulsar, a huge amount of rotation energy can be naturally injected into the GRB remnant either in the form of a Poynting flux or a relativistic particle flux, when the rotating pulsar gradually brakes down (Dai & Lu 1998; Zhang & Mészáros 2001). In this case, the energy injection is a continuous process whose timescale is determined by the braking mechanism. Another possibility is that, since the standard fireball model of GRBs resorts to internal shocks to produce the observed highly variable γ-ray light curve in the main burst phase, it is very likely that the central engine may also give birth to some late slow shells, which catch up with the main remnant only in the afterglow phase (Rees & Mészáros 1998; Kumar & Piran 2000; Sari & Mészáros 2000; Piran, Nakar, & Granot 2003; King et al. 2005). In this case, the energy supply will be completed relatively quickly, producing an essentially instantaneous energy injection.

For the rebrightening of the afterglow of GRB 030329, energy-injection is surely a potential explanation (Granot, Nakar, & Piran 2003). Actually, Granot et al. (2003) suggested that in addition to the major energy injection occurring at $t \sim 1.6$ d, there were furthermore three minor energy injection processes occurring at $t \sim 2.4$ d, 3.1 d, and 4.9 d respectively, giving birth to the observed subtle light curve variations between $(2 — 6) \times 10^5$ s.

We now fit the afterglow of GRB 030329 numerically by adopting the energy-injection model. Since the observed rebrightening at $t \sim 1.6$ d is so rapid, we believe that a quick energy-injection is necessary. In our calculation, we assume that an amount of kinetic energy that equals the initial energy (E_0) of the primary GRB ejecta is supplied into the blastwave at the observer's time $t \sim 1.1 \times 10^5$ s. For simplicity, we assume that the energy supply is completed instantly. At $t = 4 \times 10^5$ s, we notice that another energy injection at the amplitude of $0.4E_0$ is needed to account for the observed emission between 4×10^5 s and 1×10^6 s. This roughly corresponds to the 4th energy injection process suggested by Granot et al. (2003). In Granot et al.'s study, the time span of the observed light curve is $t < 9$ d. Here, when we expand the light curve to $t \sim 80$ d, we find that an additional energy injection (with $0.6E_0$) is necessary, which occurs at about 1.2×10^6 s. Our final numerical results are shown in Figure 3.

Interestingly enough, we find that the energy-injection at $t \sim 1.1 \times 10^5$ s really can produce an obvious rebrightening as expected. The energy-injection model is thus better than the two previous models at least in this aspect. The relative residual of the solid line in Figure 3 is generally less than 20%, so that the overall fit can also be evaluated as acceptable.

However, we also notice that there are still some obvious problems in the fit. First, the observed light curve shows a sharp jet break at $t \sim 0.5$ d ($\sim 4.3 \times 10^4$ s), but the theoretical light curve is simply too smooth, which leads to a systematic residual of $\sim 15\%$ during 2×10^4 s — 5×10^4 s. It has been noted that a small half-opening angle of the jet can help to make the break sharper (Wei & Lu 2000b; Huang et al. 2000a). In fact, in our current study, in order to get a break that is as sharp as possible, we have assumed a very small initial half-opening angle for the jet, i.e. $\theta_0 = 0.05$. Since the decay of the afterglow of a narrower jet is generally slightly faster, we then have to assume a relatively flat spectrum for the shock-accelerated electrons ($p = 1.9$) so as to match the observed decay rate of $F_{\rm R} \propto t^{-0.85}$ before the jet break. However the theoretical break is still too shallow. In fact the same problem also exists in Figures 1 and 2. The sharpness of the observed light curve breaks actually is a general challenge to theorists, since numerical results by a few authors have shown that the predicted light curve break usually is not so sharp (Panaitescu & Mészáros 1998; Moderski, Sikora, & Bulik 2000; Wei & Lu 2000b). With plenty of observational data points before and after the jet break, GRB 030329 will be a valuable example that can be used to study the sharpness problem carefully. These studies may help to address many important issues of GRB afterglows, such as the initial opening angle of the jet, the effect of the lateral expansion, the influence of the equal arrival time surfaces, and so on. We thus suggest that the early afterglow of GRB 030329 ($t < 10^5$ s) deserves to be paid special attention to, and further detailed numerical study should be carried out.

Secondly, although an obvious brightness enhancement is produced by the energy injection at $t \sim 1.6$ d, the theoretical rebrightening is still not rapid enough as compared with observations. As a result, we see that the relative residual reaches $\sim -20\%$ before the rebrightening, and reaches $\sim +15\%$ thereafter. Here we have already assumed an instantaneous energy injection. It is suspected that things might get even worse in reality since the energy injection will surely take some time. However, at least two factors may help to ease this unsatisfactory situation: (1) The energy injection itself may be a complicated process. For example, additional forward shocks or even reverse shocks may form when the slow shell collides with the original jet, and extra emission from these shocks may make the rebrightening more significant. But discussion of these extra emission will involve some largely uncertain conditions (such as the thickness, the composition, and the speed of the energy-injection shell), and will not be conducted here; (2) The half-opening angle of the injected shell may be another important factor. At the time of the energy injection, the

opening angle of the original jet already increases to $\theta \approx 0.15$ due to lateral expansion. In our calculation, we have assumed that the energy is supplied to the whole jet homogeneously for simplicity. But it is probable that the injected shell itself may have an opening angle much smaller than 0.15, then the energy supply will be restricted only to a small portion of the original jet, as already illustrated by Granot et al. (2003). In that case, the timescale of the rebrightening can be greatly reduced. Again, detailed consideration will involve some uncertain conditions, such as the initial opening angle and the sideways expansion of the energy-injection shell.

Thirdly, there are some subtle variations in the observed light curve for $2 \times 10^5 \mathrm{s} \leq t \leq 8 \times 10^5$ s. As suggested by Granot et al. (2003), these variations may be due to further minor energy injections. In our calculations, we do not include the second and the third energy injection events proposed by Granot et al. In fact, since our modeling is still very coarse and highly simplified, we believe that the observed fine structures will not be satisfactorily reproduced even if all the minor energy injections are incorporated. To completely solve the problem, we may need to carefully consider the factors related to the second problem as addressed above.

In short, GRB 030329 is a special but important event. Its afterglow behavior is very complicated and a satisfactory fit to the overall R-band light curve is not an easy task (Zeh, Klose, & Kann 2005). However, after comparing all the three models examined in our current study, we propose that the energy-injection model is the most appropriate one for GRB 030329, especially when the rebrightening at $t \sim 1.6$ d are taken into account.

4. Conclusion and Discussion

The optical afterglow of GRB 030329, with a notable rebrightening at $t \sim 1.6$ d, is re-examined numerically in light of three candidate models. In the density-jump model, no obvious rebrightening can be reproduced at the moment when the density increases abruptly. Additionally, the predicted flux density decreases significantly well after the density-jump, evidently in contrast with the observations. In the two-component jet model, emission from the wide component can significantly boost the afterglow and thus can roughly fit the late afterglow of GRB 030329. However, the predicted rebrightening is still far too slow when compared with observations. In fact, no obvious bump can be seen in the final theoretical light curve at $t \sim 1.6$ d at all. The energy-injection model seems to be the most preferred choice. When an amount of energy that equals the initial kinetic energy of the GRB ejecta is added instantly into the blastwave at $t \sim 1.6$ d, a marked rebrightening emerges, which, although is still not rapid enough, gives an acceptable explanation to observations.

Since the rebrightening of GRB 030329 is so rapid, we have to employ an instant energy-injection process in our calculation. In reality, this is most likely corresponding to the energy supplying process by a relatively slow shell which carries a significant amount of kinetic energy but is ejected at a comparatively late stage by the central engine. Usually, the shell is very thin, with a width of $\sim 10^6$ — 10^8 cm, just as other more rapid shells that produce internal shocks and give birth to the main GRB. The shell moves outward at approximately a constant speed in a dilute environment that has been swept by previous shells. At the observer's time $t \sim 1.6$ d, when the shell finally catches up with the main blastwave, its thickness may increase slightly, but will still reasonably be much smaller than the radius of the blastwave. Interaction of this shell with the preceding blastwave can then be completed in a short time, producing an instant energy injection.

For GRB 030329, Granot et al. (2003) suggested that there are a total of four energy-injection events within ~ 9 days after the burst trigger, which help to explain the observed variations between 10^5 s — 10^6 s. Here, when we extend the time span to $t \sim 80$ d, we identify a further energy injection event occurring at 1.2×10^6 s. In fact, similar multiple energy injections have also been suggested in another famous event, GRB 021004, by de Ugarte Postigo et al. (2005). In that case, a total of up to seven energy injections have been employed to explain the complex multiband afterglow light curves. In the standard fireball model of GRBs, afterglows are deemed to largely lose their memory of the central engine. But the energy-injection shells are valuable fossils left by the central engine. Careful study on these shells may provide important clues for the central engine and the GRB trigger mechanism.

However, GRB 030329 is a very complex event (Zeh, Klose, & Kann 2005). Even in our best fit to the optical afterglow by engaging the energy-injection model (i.e., the solid line in Figure 3), there are still some obvious problems. The observed jet break at $t \sim 0.5$ d is not satisfactorily fitted; The theoretical rebrightening at $t \sim 1.6$ d is still not rapid enough; The observed subtle light curve variations during 2×10^5 s — 10^6 s are not well accounted for. Solving these problems may need the consideration of many further details, or even substantial revision of the model. Since the observational data are unprecedentedly prolific, GRB 030329 is undoubtedly a valuable sample. We suggest that a further complete, satisfactory fit to the R-band light curve (or even multi-band observations, ranging from radio to X-rays) should deserve trying, which will definitely provide useful information on the physics of GRBs and afterglows.

Finally, we should bear in mind that the two-component jet model actually also has its own advantage when applied to GRB 030329: the emission from the wide component can potentially give a natural explanation to the very late afterglow, but in the energy-injection

model, a further energy injection process will have to be assumed for the afterglow beyond 10^6 s, which is somewhat artificial and makes us uncomfortable. The two-component jet is still a possibility, although it cannot be used to explain the rebrightening episodes. In fact, it is probable that a compound model may be taking effect in the case of GRB 030329. The event may basically be due to a two-component jet, with the narrow component accounting for the early afterglow ($t \leq 1.0 \times 10^5$ s) and the wide component accounting for the late afterglow ($t \geq 3.0 \times 10^5$ s). At the same time, an additional energy injection may happen to the narrow component at about 1.6 d, which explains the observed rebrightening. It is interesting to note that another novel idea that may possibly reconcile the two-component jet model and the energy-injection process has also been proposed by Resmi et al. (2005) recently. They suggested that there might be only one narrow jet initially in GRB 030329. But at a time around or before ~ 1.5 d, a possible re-energization event may take place, refreshing the initial narrow jet into a second, "wide" jet. They noted that the half opening-angle of the initial narrow jet, due to side expansion, has already increased to a value which equals that required for the wide jet. While the scenario itself is also plausible, the detailed physical process still needs to be clarified extensively.

We thank the anonymous referee for many valuable comments that lead to an overall improvement of this study and especially for helping us to access the observational data of GRB 030329. This research was supported by a RGC grant of the Hong Kong Government, and also partly supported by the Special Funds for Major State Basic Research Projects, the National Natural Science Foundation of China (Grants 10233010, and 10221001), and the Foundation for the Author of National Excellent Doctoral Dissertation of P. R. China (Project No: 200125).

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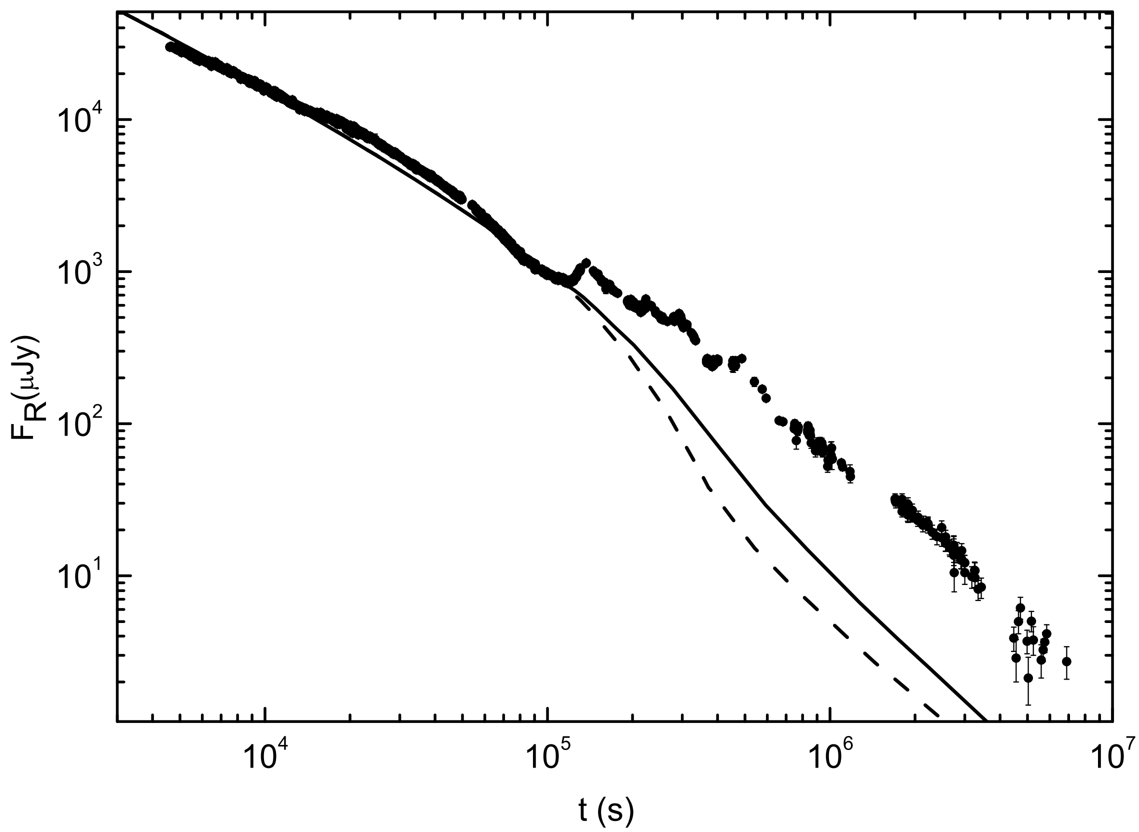

Fig. 1.— An illustration of our fit to the R-band afterglow light curve of GRB 030329 by using the density-jump model. Observed points correspond to pure afterglow emission, derived by subtracting the host galaxy contribution and the supernova contribution from the data of Lipkin et al. (2004). In the solid line, the number density of the circumburst medium is assumed to increase abruptly from 2 cm^{-3} to 20 cm^{-3} at the observer's time $t = 1.1 \times 10^5$ s. In the dashed line, the density increases from 2 cm^{-3} to 200 cm^{-3} at the same time. Other parameters involved in this figure have been given in §3.1 . In both cases, the model fails to reproduce the observed rebrightening at $t \sim 1.6$ d and the observed flux excess thereafter.

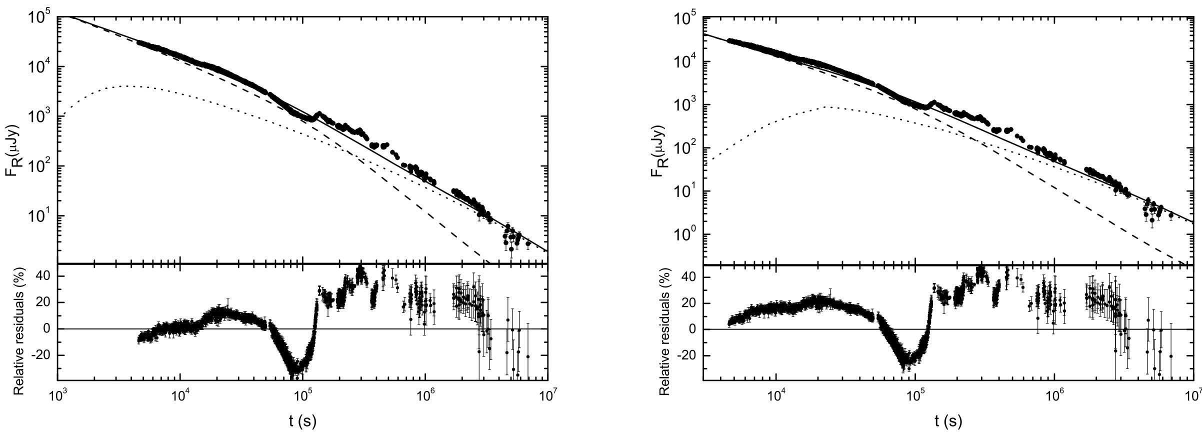

Fig. 2.— (a) Our best fit to the R-band afterglow light curve of GRB 030329 using the two-component jet model. Observed points correspond to pure afterglow emission, derived from the data of Lipkin et al. (2004). The dashed line corresponds to emission from the narrow component, the dotted line corresponds to emission from the wide component, and the solid line is the total light curve. In the lower panel, the relative residual of the fit is plotted. Parameters involved in this figure have been given in §3.2 . (b) Same as (a), except that the wide component is now assumed to be a hollow cone since its central portion is occupied by the narrow component. Note that in both (a) and (b), no obvious rebrightening can be seen in the modeled light curves at $t \sim 1.6$ d, thus the model is not preferred by observations.

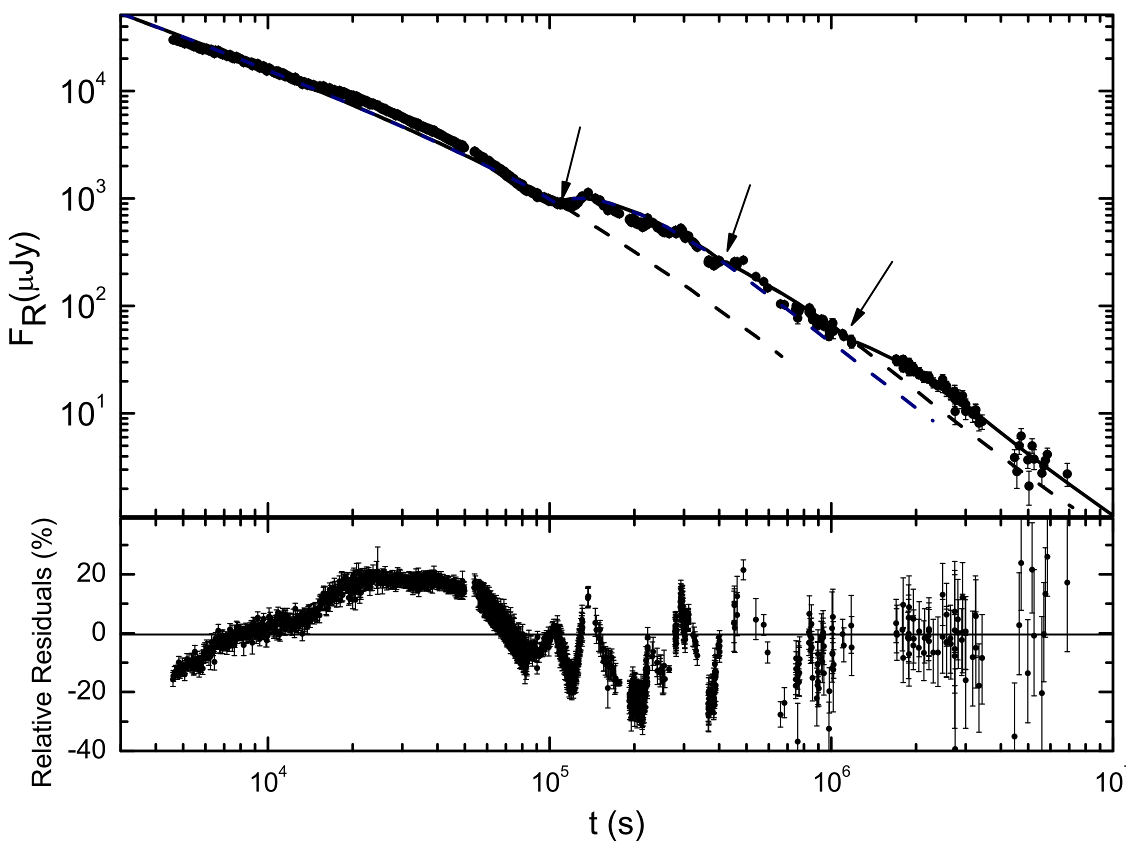

Fig. 3.— Our fit to the R-band afterglow light curve of GRB 030329 in light of the energy-injection model. Observed points correspond to pure afterglow emission, derived from the data of Lipkin et al. (2004). The solid line corresponds to our best fit by engaging 3 energy injections, which occur at $t = 1.1 \times 10^5$ s, 4.0×10^5 s, and 1.2×10^6 s, as marked by arrows. The injected energies are 1.0 E_0, 0.4 E_0, and 0.6 E_0, respectively. For comparison, the dashed lines illustrate the theoretical afterglows when no further energy is supplied. Parameters involved in this figure are the same as those in Figure 1. In the lower panel, the relative residual of the solid line is plotted.